

# **Joining and Assembly of Silicon Carbide-based Advanced Ceramics and Composites for High Temperature Applications**

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## **Abstract**

Silicon carbide based advanced ceramics and fiber reinforced composites are under active consideration for use in a wide variety of high temperature applications within the aeronautics, space transportation, energy, and nuclear industries. The engineering designs of ceramic and composite components require fabrication and manufacturing of large and complex shaped parts of various thicknesses. In many instances, it is more economical to build up complex shapes by joining simple geometrical shapes. In addition, these components have to be joined or assembled with metallic sub-components. Thus, joining and attachment have been recognized as enabling technologies for successful utilization of ceramic components in various demanding applications. In this presentation, various challenges and opportunities in design, fabrication, and testing of high temperature joints in ceramic matrix composites will be presented. Silicon carbide based advanced ceramics (CVD and hot pressed), and C/SiC and SiC/SiC composites, in different shapes and sizes, have been joined using an affordable, robust ceramic joining technology (ARCJoinT). Microstructure and high temperature mechanical properties of joints in silicon carbide ceramics and CVI and melt infiltrated SiC matrix composites will be reported. Various joint design philosophies and design issues in joining of ceramics and composites will be discussed.

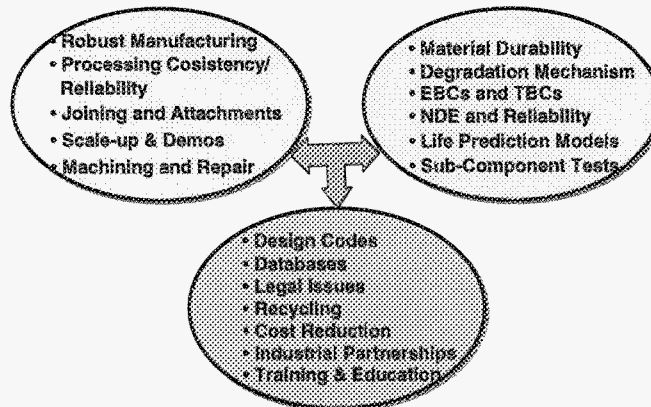
# **Joining and Assembly of Silicon Carbide-based Advanced Ceramics and Composites for High Temperature Applications**

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## **Outline**

- **Background and Rationale**
- **Challenges in Joining of Ceramics and CMCs**
  - *Joint Design, Testing, and Data Analysis*
  - *Long Term Durability*
- **ARCJoinT Technology**
  - **Silicon Carbide Ceramics**
    - *Reaction Bonded, Sintered, and CVD SiC*
  - **Ceramic Matrix Composites**
    - *CVI C/SiC Composites*
    - *MI SiC/SiC Composites*
- **Results and Discussion**
  - **Monolithic SiC Ceramics**
  - **CVI C/SiC Composites**
    - (*effect of surface roughness, temperature*)
  - **MI SiC/SiC Composites**
    - (*flexure testing, tensile testing of lap joints, data analysis*)
- **Summary and Conclusions**

## Key Technical Challenges to Insertion of Advanced Ceramic Materials



Interactive and Iterative Approach Across Disciplines Required

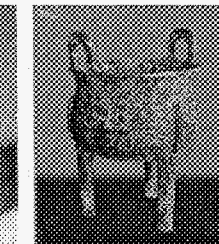
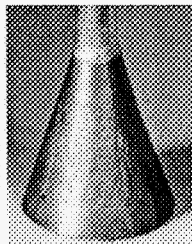
## Joining and Assembly Technologies Through the Ages



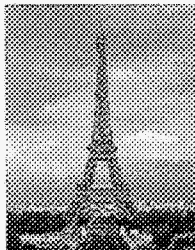
**Prehistoric Civilization**  
Attachment Technology for  
Hunting Tools



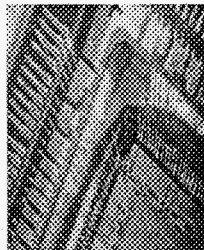
**Bronze Age (7000-1000 BC)**  
Brazing and Soldering Used for  
Jewelry and Domestic Articles



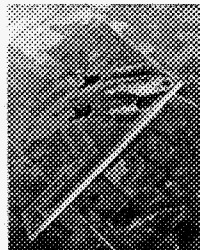
**Shang Dynasty**  
Ceremonial Vessel - 1100 BC



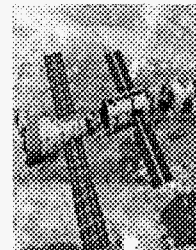
**Eiffel Tower, Paris**  
1889



**Microelectronics  
Packaging**



**Aerospace and  
Defense**



**International Space  
Station**

### **Need for Joining and Assembly Technologies**

- **Joining is an enabling technology for utilization of advanced ceramics and composites in high temperature applications.**
  - **Aerospace Systems**
    - *Aerospace and Space Propulsion Components (Combustor Liners, Exhaust Nozzles, Nozzle Ramps, Turbopump Blisks)*
  - **Non-Aerospace Systems**
    - *Nuclear Industries, Land Based Power Generation, Process Industries, Heat Exchangers, Recuperators, Microelectronic Industries (Diffusion Furniture, Boats)*
- **The development of ceramic joining and assembly capability will allow the application of advanced ceramics and composites technology in a timely manner.**

### **Technical and Performance Requirements for Joined Structures and Joining Technology**

- **Joint properties comparable to base materials.**
  - **Use temperature > 1200 °C**
  - **Good mechanical strength**
  - **Oxidation and corrosion resistance**
  - **Low CTE mismatch to minimize residual stresses**
  - **Good thermal shock resistance**
- **Leak tight joints.**
- **Practical, reliable, and affordable technique adaptable to in-field installation, service, and repair.**

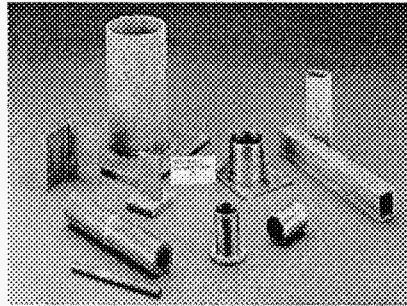
## Joining of Ceramic Components Using Affordable, Robust Ceramic Joining Technology (ARCJoinT)

Joining of Ceramic Components  
Using Affordable, Robust Ceramic  
Joining Technology (ARCJoinT)

ARCJoinT

Affordable, Robust, and  
Customizable Joining  
Technology

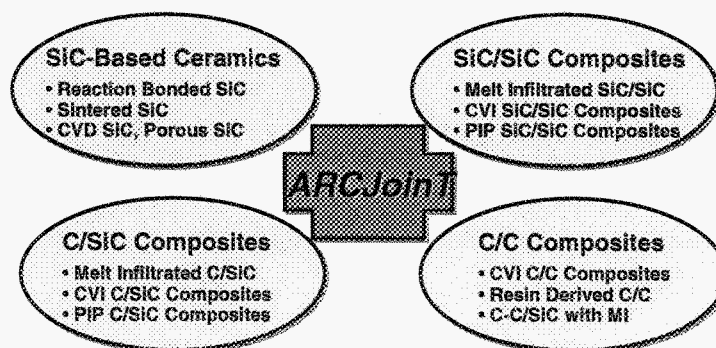
1999 R&D 100 Award  
2000 NorTech Innovation Award



### Advantages

- Joint interlayer properties are compatible with parent materials.
- Processing temperature around 1200-1450°C.
- No external pressure or high temperature tooling is required.
- Localized heating sources can be utilized.
- Adaptable to in-field installation, service, and repair.

## ARCJoinT is Currently Being Used to Join and Repair a Wide Variety of Ceramic and Composite Materials



- Composites with Different Fiber Architectures and Shapes
- Ceramics with Different Shapes and Sizes

## Experimental Procedures

### Materials:

- RB-SiC (REFEL), Sintered SiC (Hexoloy-SA)

### Microstructural Analysis:

- TEM, SEM, Optical Microscopy

### Mechanical Testing:

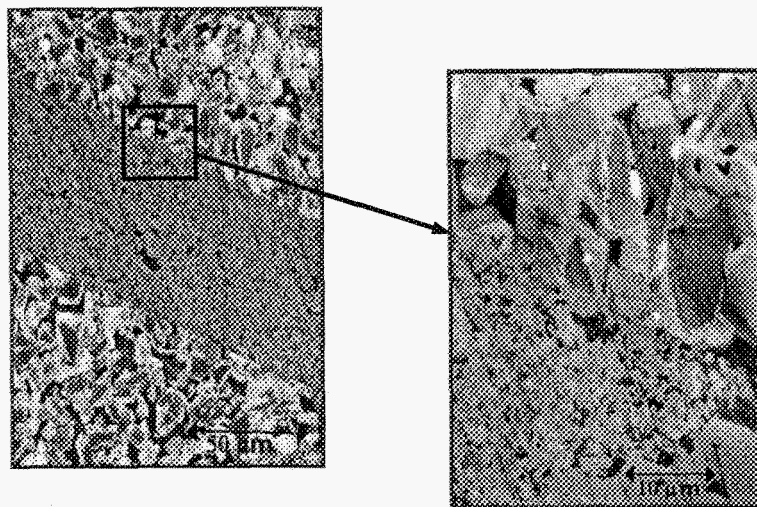
- Compression at a constant strain rate ( $2 \times 10^{-5} \text{ s}^{-1}$ )
- Temperatures ranging from 1235°C to 1425°C, in air
- Joint is formed 45° with the compression axis (scarf butt geometry)

**Advantages:** Tests require small amount of materials  
Stress and strain can be directly measured

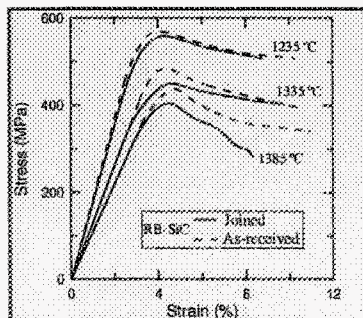
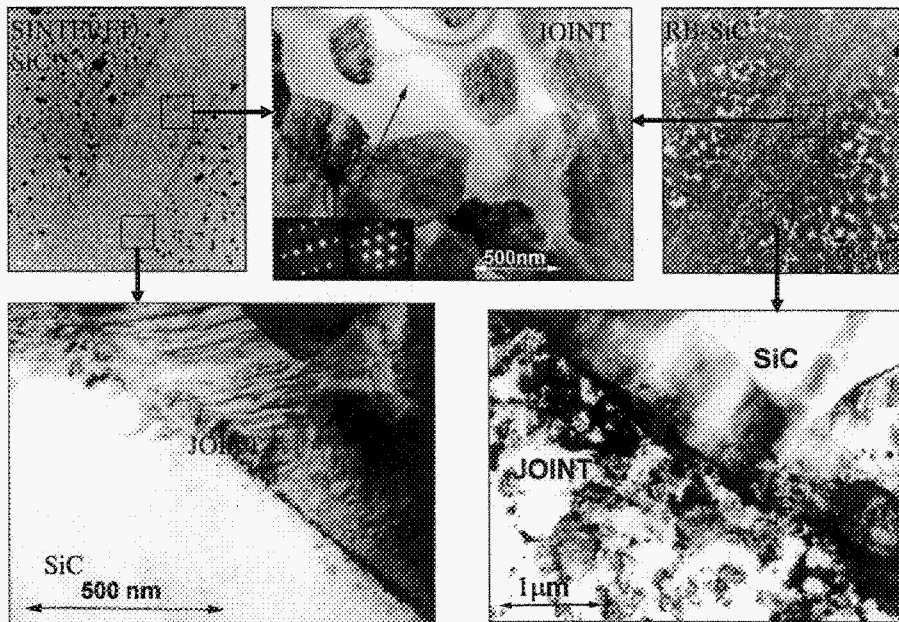
### Joint thickness:

- Refel RB-SiC:  $58.2 \pm 1.2 \text{ } \mu\text{m}$
- Hexoloy-SA SiC:  $63.1 \pm 0.6 \text{ } \mu\text{m}$

## SEM Micrograph of As-Fabricated Joints in RB-SiC

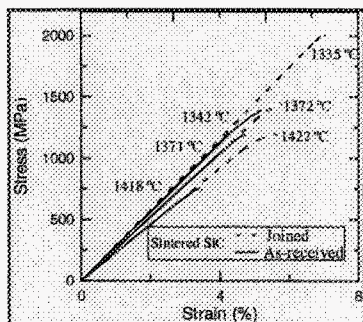


### TEM Analysis of Reaction Formed Joints

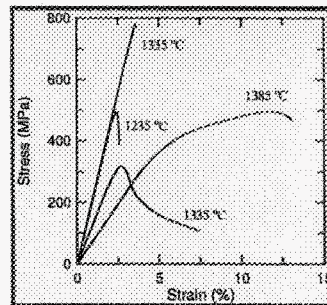


**Stress vs Strain Behavior as a Function of Temperature**

**A**

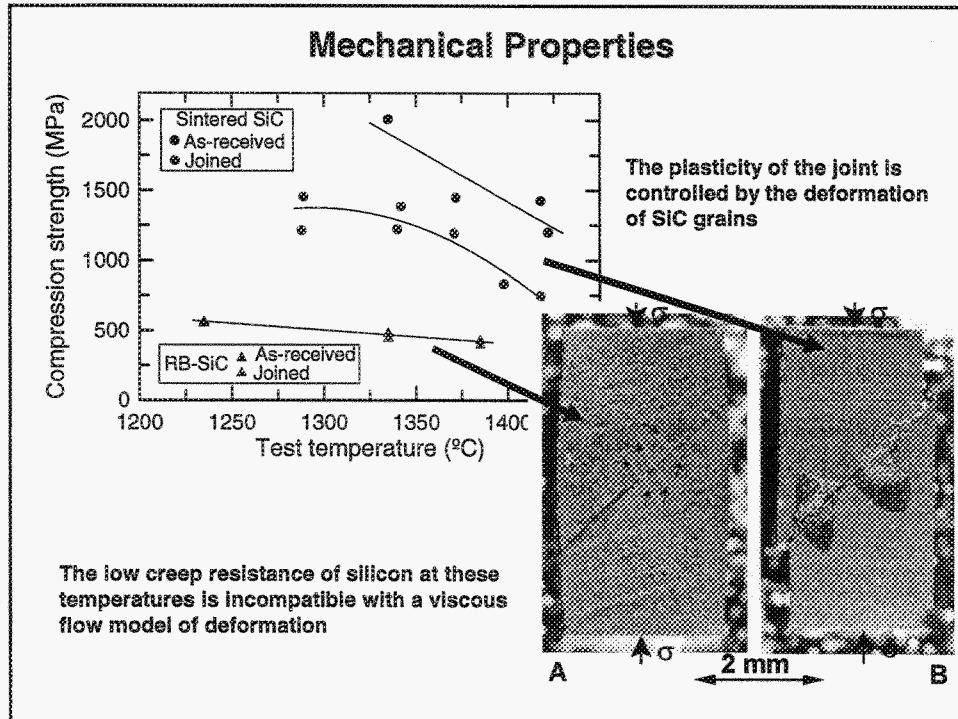


**B**



Sintered SiC where a lower pressure than in A) and B) has been used during fabrication





## Challenges in Joining of Ceramic Matrix Composites

### • Joint Design

- High elastic modulus of ceramic joint materials provide significant challenges to joint design and characterization.
- Understanding of stress state in the joints.

### • Materials

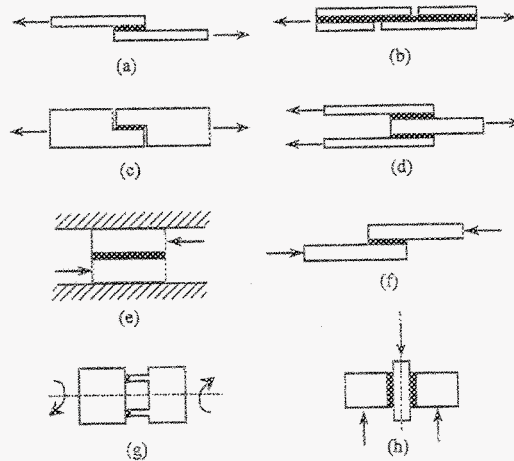
- Optimization of in-plane tensile properties of CMCs by engineering the fiber/matrix interface are accomplished at the expense of interlaminar properties. Weak interfaces complicate joint properties and performance
  - Composition and microstructure
  - Bonding and adhesion
  - Testing and data analysis
- High elastic modulus ceramic joint materials.

### • Applications

- Time dependent thermomechanical properties of joints.
- Environmental effects on joint properties.

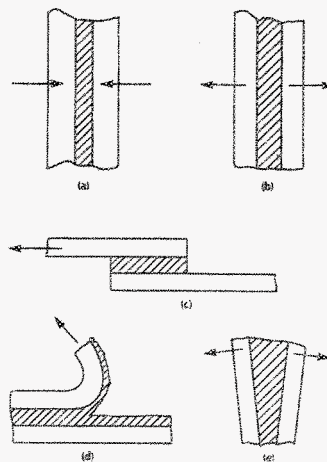


## Technical Challenges in Design and Selection of Ceramic Joints



*Different Types of Shear Tests*

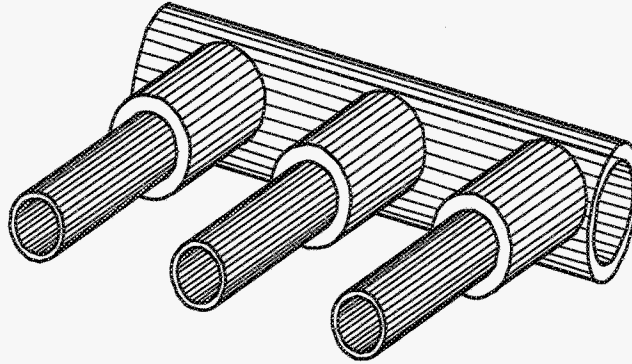
## Technical Challenges in Design of Ceramic Joints



*Typical  
Ceramic  
Joints will  
have  
Combination  
of Stresses  
Under  
Operating  
Conditions*

(a) Compression; (b) Tension; (c) Shear; (d) Peel; (e) Cleavage

### Schematic of Ceramic Tubes Joined to Ceramic Composite Manifold in a Heat Exchanger

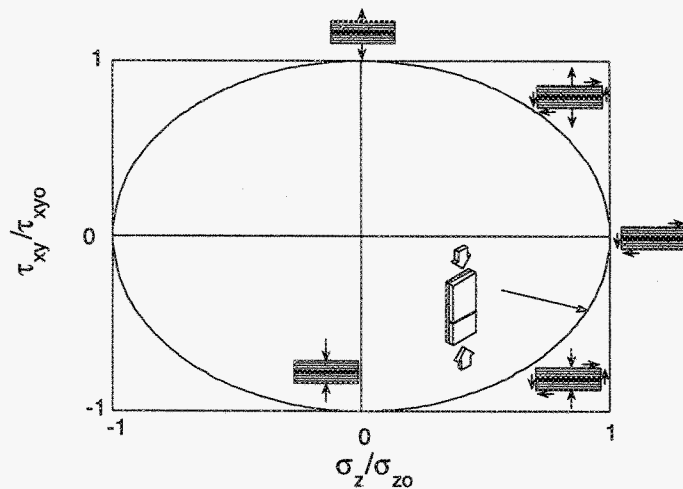


Stresses in the Joint Regions Involve Multiaxial States of Stress  
(e.g., Normal Plus Shear Stresses)

M. Singh and E. Lara-Curzio, J. Engineering for Gas Turbines and Power, 123 (2001) 288-292.

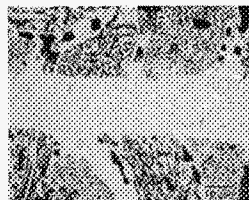
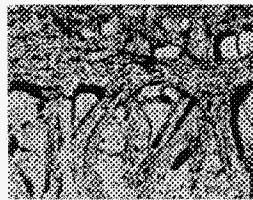
### Joint Design Map Where Shear and Normal Stresses Have Been Normalized by Virgin Isothermal Joint Strengths

(The Envelope Defines the Strength of the Joint)

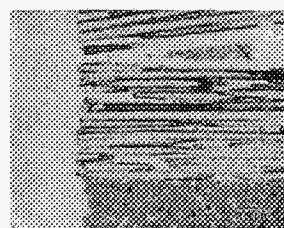
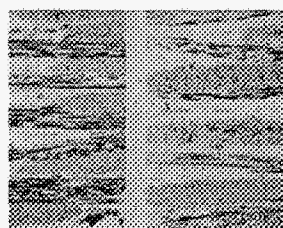
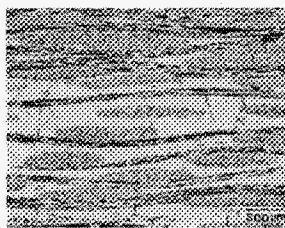


M. Singh and E. Lara-Curzio, J. Engineering for Gas Turbines and Power, 123 (2001) 288-292.

### Typical Microstructure of Joined SiC-Based Ceramic Matrix Composites



Novoltex® C/SiC Composite    Joined Novoltex® Composite



MI C/SiC Composite

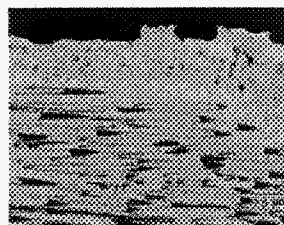
Joined MI C/SiC Composite

Joint-Composite Interface

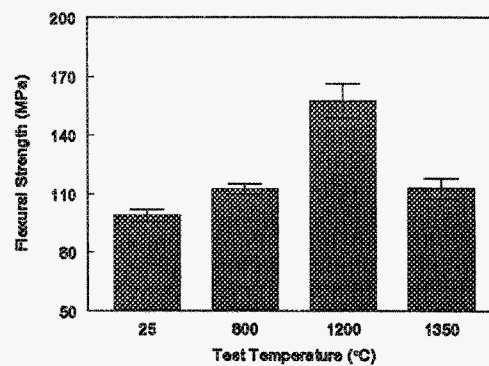
### Microstructure and Mechanical Properties of Joined MI HI-Nicalon/BN/SiC Composites



MI SiC/SiC Composite

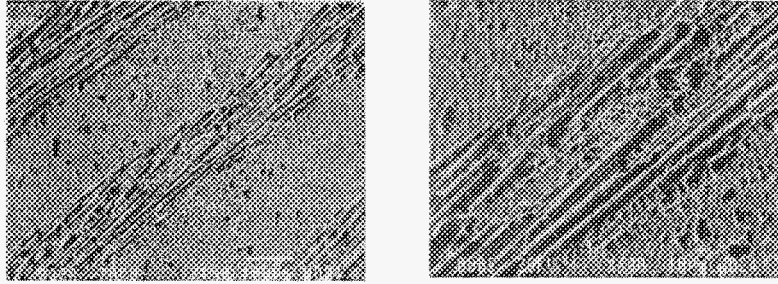


Joint-Composite Interface

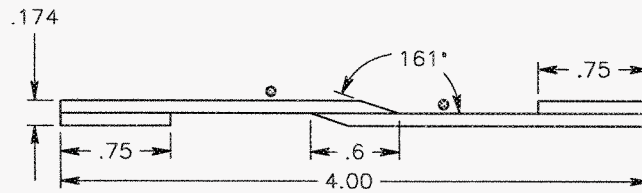


Flexural Strength of Joined SiC/SiC Composites

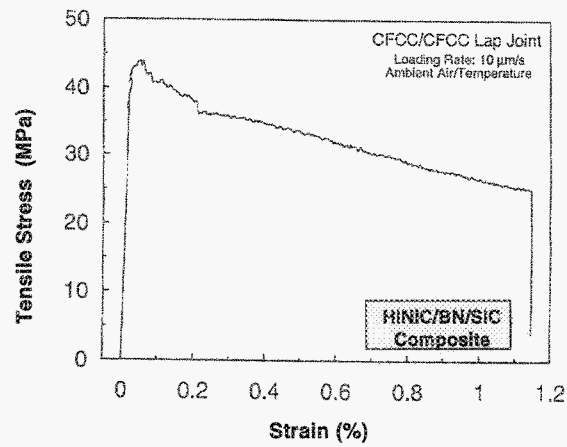
**SEM Micrographs of Joints in MI SiC/SiC Composites  
Tested at 1200°C**



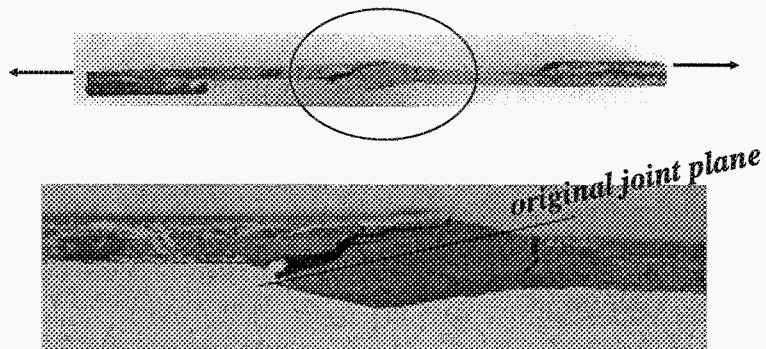
**Tensile Specimen Geometry of  
Single Lap Joined MI SiC/SiC Composites**



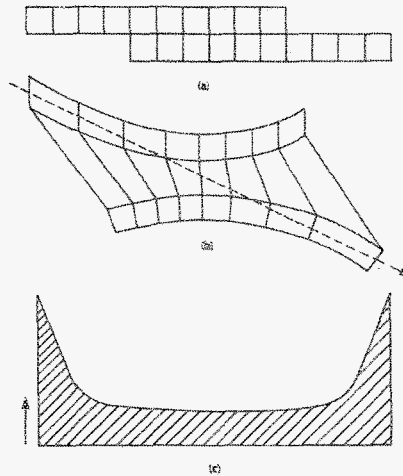
### Tensile Stress vs Strain Behavior of Single Lap Joined MI SiC/SiC Composites



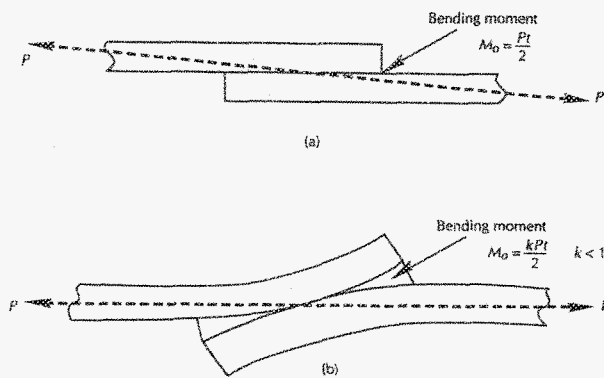
### Fracture Behavior of Single Lap Joints in Melt Infiltrated SiC/SiC Composites



### Shear Stress Distribution in a Single Lap Joint



### Goland and Reissner's Bending Moment Factor in Single Lap Joints



# Stress Distribution in Single Lap Joints Subjected to Tensile Loading (Goland and Reissner)

The expressions for the adhesive and transverse stresses, normalized by the applied tensile stress, are:

$$\frac{\tau_o}{\sigma_{appl}} = -\frac{1}{8} \frac{t}{c} \left[ \frac{\beta c}{t} (1+3k) \frac{\cosh\left(\frac{\beta c x}{t}\right)}{\sinh\left(\frac{\beta c}{t}\right)} + 3(1-k) \right] \quad (1)$$

$$\begin{aligned} \frac{\sigma_o}{\sigma_{appl}} = & \frac{t^2}{c^2} \frac{1}{\Delta} \left[ \left( R_2 \lambda^2 \frac{k}{2} + \lambda k' \cosh \lambda \cos \lambda \right) \cosh \left( \lambda \frac{x}{c} \right) \cos \left( \lambda \frac{x}{c} \right) + \right. \\ & \left. \left( R_1 \lambda^2 \frac{k}{2} + \lambda k' \sinh \lambda \sin \lambda \right) \sinh \left( \lambda \frac{x}{c} \right) \sin \left( \lambda \frac{x}{c} \right) \right] \quad (2) \end{aligned}$$



**Where**

$$\beta^2 = \frac{8 G_c t}{E \eta} = \frac{4 E_c t}{E \eta (1 + \nu_c)} \quad (3)$$

$$M_o \approx k \frac{T t}{2} = \frac{k p t^2}{2} \quad (4)$$

$$k = \frac{1}{1 + 2 \sqrt{2} \tanh \left( \frac{\xi c}{2 \sqrt{2}} \right)} \quad (5)$$

$$\xi = \sqrt{\frac{12 (1 - \nu^2) T}{E t^3}} \quad (6)$$

$$\gamma^4 = 6 \frac{Ec}{E} \frac{t}{\eta} \quad (7)$$

$$\lambda = \gamma \frac{c}{t} \quad (8)$$

$$R_1 = \cosh \lambda \sin \lambda + \sinh \lambda \cos \lambda \quad (9)$$

$$R_2 = \sinh \lambda \cos \lambda - \cosh \lambda \sin \lambda \quad (10)$$

$$\Delta = \frac{1}{2} (\sinh 2\lambda + \sin 2\lambda) \quad (11)$$

### Stress Distribution in Single Lap Joints Subjected to Tensile Loading (Goland and Reissner)

The geometric and materials parameters  $c$ ,  $t$ ,  $E$ ,  $\nu$ ,  $E_c$ , and  $\nu_c$  are given below. Based on this analysis, the experimental tensile data, the geometry of the specimen, and the following elastic properties:

$$\begin{aligned} E_{\text{substrate}} &= 300 \text{ GPa} \quad (E) \\ \nu_{\text{substrate}} &= 0.15 \quad (\nu) \\ E_{\text{adhesive}} &= 350 \text{ GPa} \quad (E_c) \\ \nu_{\text{adhesive}} &= 0.2 \quad (\nu_c) \end{aligned}$$

The maximum transverse and adherent shear stresses were found to be:

$$\begin{aligned} \frac{\tau_o}{\sigma_{\text{appl}}} &= 4.2 \\ \frac{\sigma_o}{\sigma_{\text{appl}}} &= 5.5 \end{aligned}$$

### Maximum Transverse and Joint Shear Stresses in MI SiC/SiC Composites Obtained from Goland and Reissner Analysis

#### For Tensile Stresses of 45 and 42 MPa:

- Shear Stress:

$$\tau_o = 4.2 \cdot \sigma_{\text{appl}}$$

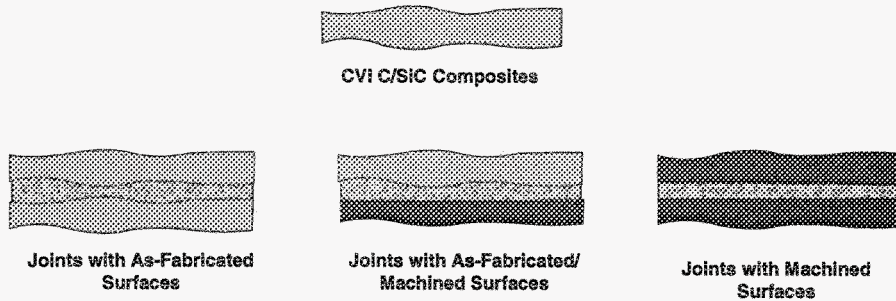
189 MPa and 176.4 MPa

- Transverse Stress:

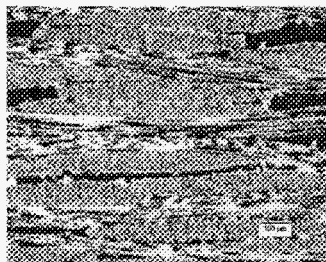
$$\sigma_o = 5.5 \cdot \sigma_{\text{appl}}$$

247.5 MPa and 231 MPa

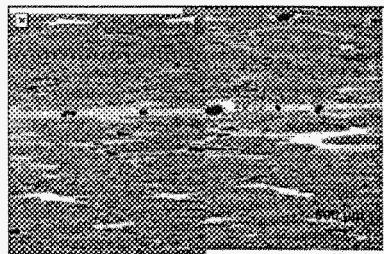
## Effect of Surface Roughness on the Shear Strength of Joined CVI C/SiC Composites



## Microstructure of As-Fabricated and Joined CVI C/SiC Composites



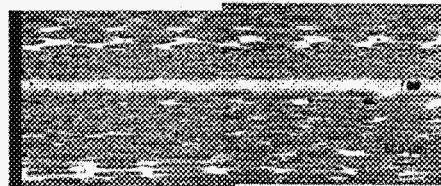
CVI C/SiC Composites  
(as fabricated)



Joined CVI C/SiC Composites  
(both surfaces machined)



Joined CVI C/SiC Composites  
(one surface machined and  
one surfaces as received)



Joined CVI C/SiC Composites  
(both surfaces as received)

## Specimen Geometry Used for Compression Double-Notched Shear Tests



ASTM C 1292-95a (RT) and ASTM C 1425-99 (HT)

### Specimen Dimensions

Specimen length (L) : 30 mm ( $\pm 0.10$  mm)

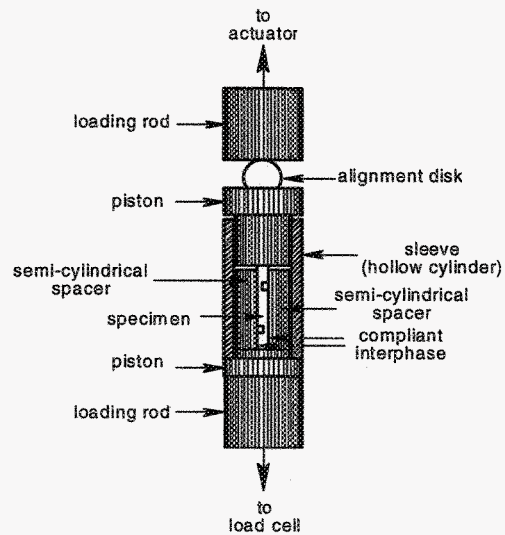
Distance between notches (h) : 6 mm ( $\pm 0.10$  mm)

Specimen width (W) : 15 mm ( $\pm 0.10$  mm)

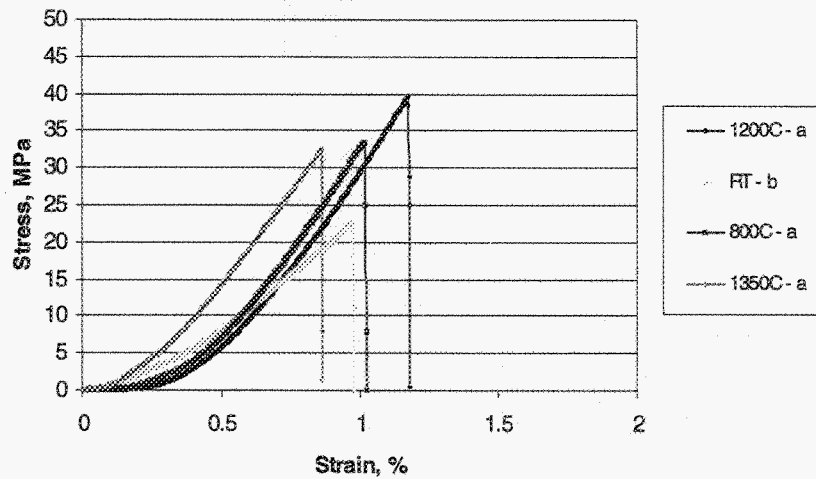
Notch width (d) : 0.50 mm ( $\pm 0.05$  mm)

Specimen thickness (t) : ---

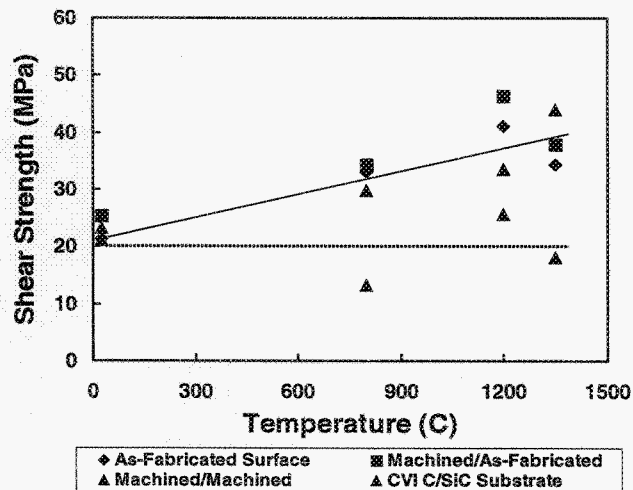
## Schematic of Test Fixture Used for Compression Double-Notched Shear Tests



### Typical Behavior of Joints During Shear Tests



### Compression Double Notch Shear Strength of Joined CVI SiC Composites at Different Temperatures



- Shear strength of joints increases with temperature and is higher than the CVI SiC composite substrate.
- No apparent influence of surface condition on the shear strength of joints.

### **Summary and Conclusions**

- The ARCJoinT process has been used to make several types of joints in SiC, C/SiC, and SiC/SiC composites.
- The strength of REFEL RB-SiC material containing a joint is not limited by the joint strength but by the strength of the bulk (parent) material. The strength of Hexoloy SiC joint is limited by the joint strength.
- In C/SiC composites, whether the joined surfaces are as-received (rough) or machined (smooth) has no effect on the shear strength of the joint. Furthermore, the shear strength of all joints exceeds that of the as-received C/SiC at elevated temperatures up to 1350 C.
- High elastic modulus of ceramic joints and weak interfaces in composite materials provide significant challenges to joint design and are critical to joint properties and performance.
- A combination of tensile, shear, and flexural testing of joints coupled with fracture mechanics based design and analysis is needed to generate useful engineering design data.
- Time dependent high temperature thermomechanical properties are critical for the successful utilization of ceramic joining technology for advanced ceramics and fiber reinforced composite materials.